

## Climate Change in the Hydrometeorological Parameters of the Black and Azov Seas (1980–2020)

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Received June 15, 2021; revised June 28, 2021; accepted August 17, 2021

**Abstract**—To study the nature of climate change in the hydrometeorological parameters of the Black and Azov Seas—surface air temperature (SAT), sea surface temperature (SST), ice cover, and sea level—under conditions of ongoing global warming, we used reanalyses and remote sensing data, as well as information from known publications of recent years. It was found that against an increase in SAT over the Black–Azov Sea region (+0.053°C/year in 1980–2020) and SST of the Black Sea (+0.052°C/year in 1982–2020), the values of these parameters in the 2000s differ significantly from those in the 1980s–1990s: the maximum average monthly summer and minimum average monthly winter temperatures have increased, as well as the number of mild winters. The average annual SST of the Black Sea, which practically did not exceed 15°C in the 1980s–early 1990s, has exceeded 16°C in most cases since 2010 (maximum 16.71°C in 2018). In the 2010s, the average monthly winter minima, with the exception of the winters of 2011/2012 and 2016/2017, did not fall below 8°C. A consequence of the increase in winter temperatures was a decrease in the ice concentration in the Sea of Azov (the trend of the mean monthly concentration is –1.2%/10 years). From about 2004–2010 in the Black Sea and since 2004 in the Sea of Azov, the tendency towards increase in their levels (on average) has been replaced by a slight decrease, so that the average positive trends for the period 1993–2020 (+0.32 ± 0.16 cm/year in the Black Sea and +0.21 ± 0.05 cm/year in the Sea of Azov) were approximately 2.5 times less than in 1993–2012. The reason for this decrease in levels (on average) in the last 10–15 years was apparently a decrease in the incoming part of the freshwater balance of both seas, which is indirectly confirmed by the observed increase in salinity of their waters.

**Keywords:** Black Sea, Sea of Azov, regional climate change, surface air temperature, sea surface temperature, ice cover, sea level

**DOI:** 10.1134/S0001437021060060

### INTRODUCTION

The semienclosed Black and Azov Seas, connected by the Kerch Strait and the system of Turkish straits with the Mediterranean Sea and then through the Strait of Gibraltar with the Atlantic Ocean, are characterized by significant interannual variability of their hydrometeorological parameters. The important national economic and military-strategic importance of these southern seas of Russia, in particular, problems of ecology, tourism, fishing, coastal infrastructure, and shipping, make, taking into account this variability, it extremely important to continuously monitor such hydrometeorological parameters for these seas as the water and air temperatures, ice cover (area covered by ice of any concentration, as a percentage of the total sea area), sea level, and their determining factors.

The long-term variability of these hydrometeorological parameters in different time periods has the

focus of many studies based on available field data and satellite measurements. A generalization of the known research results on this problem, limited mainly to 2012, is contained in [14]. It is shown, in particular, that in 1982–2009, the average annual surface temperature (SST) of the Black Sea as a whole, according to satellite data, increased at an average rate of +0.06°C/year, while over the longer time interval from 1938 to 2009, the trend of the average annual SST, e.g., at the Gelendzhik hydrometeorological station (HMS) [19] was significantly lower (+0.009°C/year) due to the small temperature change before the 1970s. The average annual SST of the Sea of Azov from the 1920s to the 1980s changed little, but in 1988–2000, a significant trend was observed (+0.06°C/year) [8]. The water temperature trend for the warm period of April–November in the Sea of Azov in 1982–2009 was +0.06°C/year, estimated from satellite data [14]. The rise in SST in both seas has

been associated with global warming since the mid-1970s. (Note that against a long-term positive SST trend in this period, in the years 1982–1993, the SST trend was negative,  $-0.03^{\circ}\text{C}/\text{year}$ , due to low average annual SST values in 1985, 1987, and 1993 [30].)

From 1993 to 2012, the rate of the rise in level of the Black and Azov Seas also significantly increased [14]. The 1993–2012 average rate of rise in the Black Sea level was  $+0.82 \pm 0.18$  cm/year, which is four to five times higher than  $+0.17$ – $0.18$  cm/year for the 1920s to the mid-1990s [6, 21]. In the Sea of Azov in 1993–2012 the positive linear trend of the level was  $+0.54 \pm 0.04$  cm/year, while the average rate of the rise in level from the 1920s to 1985 was approximately half that ( $+0.24$  cm/year) [22]). The rise in levels of both seas since the mid-1970s (on average) was caused by an increase in the input component of their water balance and a rise in the level of the World Ocean as a result of global warming.

Currently, global warming and the associated rise in the level of the World Ocean, mainly due to the melting of glaciers and the ice sheets of Greenland and Antarctica [40], continue. According to NASA's Goddard Institute for Space Studies (2021) GISS Surface Temperature Analysis (GISTEMP v4), the last 7 years were the warmest on Earth, while the years with the largest global temperature anomalies (relative to the average for the period of 1951–1980) were 2016 and 2020. The average rate of the rise in World Ocean level increased in the second decade of the 21st century: from  $+3.2$  mm/year in 1998–2015 up to  $+3.6$  mm/year in 2006–2015 [40].

This article examines the seasonal and interannual variability and linear trends in surface air temperature (SAT), sea surface temperature (SST), and ice cover in the Black and Azov Seas in the period from 1980/1982 to 2020, as well as the levels of these seas from 1993 to 2020 based on freely available databases. The obtained trends of the hydrometeorological parameters are compared with those estimated earlier for 1982–2009/2012 [14] and relevant information from publications in recent years.

## MATERIALS AND METHODS

The analysis used the time sequences of monthly average values of the studied parameters. The average monthly air temperatures at a height of 2 m from the surface in region of the Black and Azov Seas for 1980–2020, obtained from the NASA MERRA-2 database on a  $0.5^{\circ}$  latitude  $\times$   $0.625^{\circ}$  longitude grid [29] and averaged over the space within  $40^{\circ}$ – $48^{\circ}$  N and  $27^{\circ}$ – $42^{\circ}$  E. The average monthly SST data for 1982–2020 were obtained by averaging the daily average data of the original NOAA OI SST v2 high resolution dataset on a  $0.25^{\circ} \times 0.25^{\circ}$  grid [38]. These monthly average data were then averaged over the water area of the Black Sea within  $41^{\circ}$ – $47^{\circ}$  N and  $27^{\circ}$ – $42^{\circ}$  E. For the

Sea of Azov, which is completely or partially covered with ice from December to March, a time sequence of monthly average SST values was not generated, and only data from known publications of recent years were used for the analysis.

Based on the monthly average SAT data of the Black Sea–Sea of Azov region and the Black Sea SST at each grid point, the average annual variation for the periods under consideration was calculated. Then, this average annual variation at each grid point is subtracted from the data to obtain the average monthly anomalies with respect to the average annual variation (hereinafter referred to simply as anomalies), from which the linear trend of the parameter was calculated.

The linear trends were calculated using the least squares method. A low-pass Butterworth filter was used. The graphs of changes in anomalies are plotted on the graphs of changes in the parameters themselves, so that the average value for anomalies (equal to zero) coincides with the average SAT and SST values for the period under consideration; the scales are shown on one scale.

The average monthly ice concentration values in the Sea of Azov were obtained by averaging the daily average values from the CMEMS EUMETSAT OSI SAF SEAICE\_GLO\_SEAICE\_L4\_REP\_OBSERVATIONS\_011\_009 dataset on a grid of approximately 12.5 km for 1980–2020 [28]. The average monthly data were averaged over the Sea of Azov within  $45.25^{\circ}$ – $47.5^{\circ}$  N,  $34.5^{\circ}$ – $39.5^{\circ}$  E.

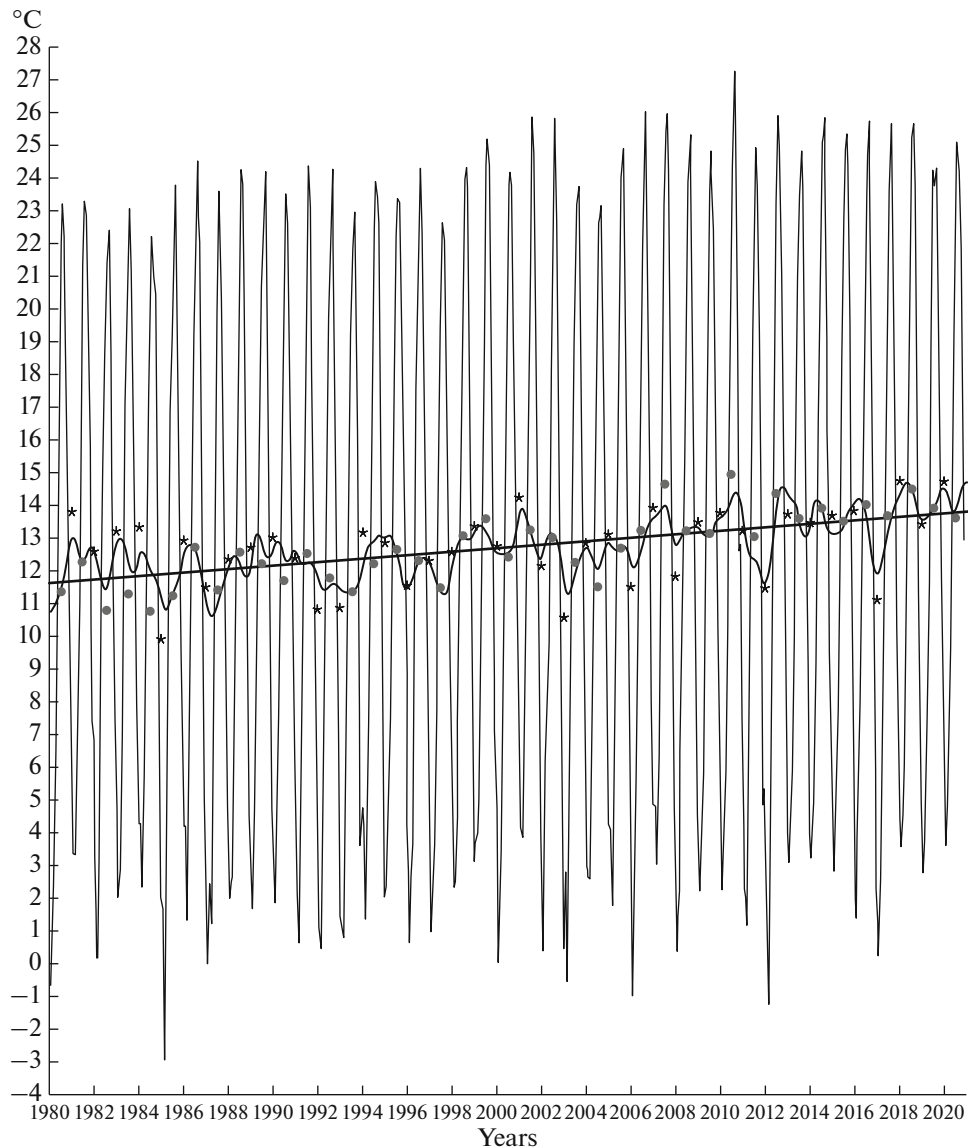
To analyze the interannual variability of the Black and Azov Seas (January 1993–December 2020), we used the time variability of sea level anomalies calculated from the data of along-track altimetry measurements of the TOPEX/Poseidon (T/P) and Jason 1/2/3 (J1/2/3) satellites. The satellite altimeter data were processed with software of the Integrated Satellite Altimetry Database, developed at the Geophysical Center RAS (see [16, 18]).

## RESULTS AND COMPARISON WITH DATA OF KNOWN PUBLICATIONS

### *SAT over the Black Sea–Sea of Azov region*

Trends in SAT changes over the Black and Azov Seas, with some regional differences, are basically similar [14]. Therefore, in this study, the SAT trend was estimated over the Black Sea–Sea of Azov region as a whole ( $40^{\circ}$ – $48^{\circ}$  N and  $27^{\circ}$ – $42^{\circ}$  E).

Figure 1 gives an idea of the seasonal and interannual variability of the mean monthly SAT in this region over a 41-year period (from January 1980 to December 2020). The linear positive SAT trend for this period was  $+0.053^{\circ}\text{C}/\text{year}$ . This estimate agrees well with measurements at the Gelendzhik HMS: from 1987 to 2017, the SAT trend was  $+0.051^{\circ}\text{C}/\text{year}$ , while for 82 years, from 1935 to 2017, the growth in SAT occurred at a three times lower rate of  $+0.017 \pm$



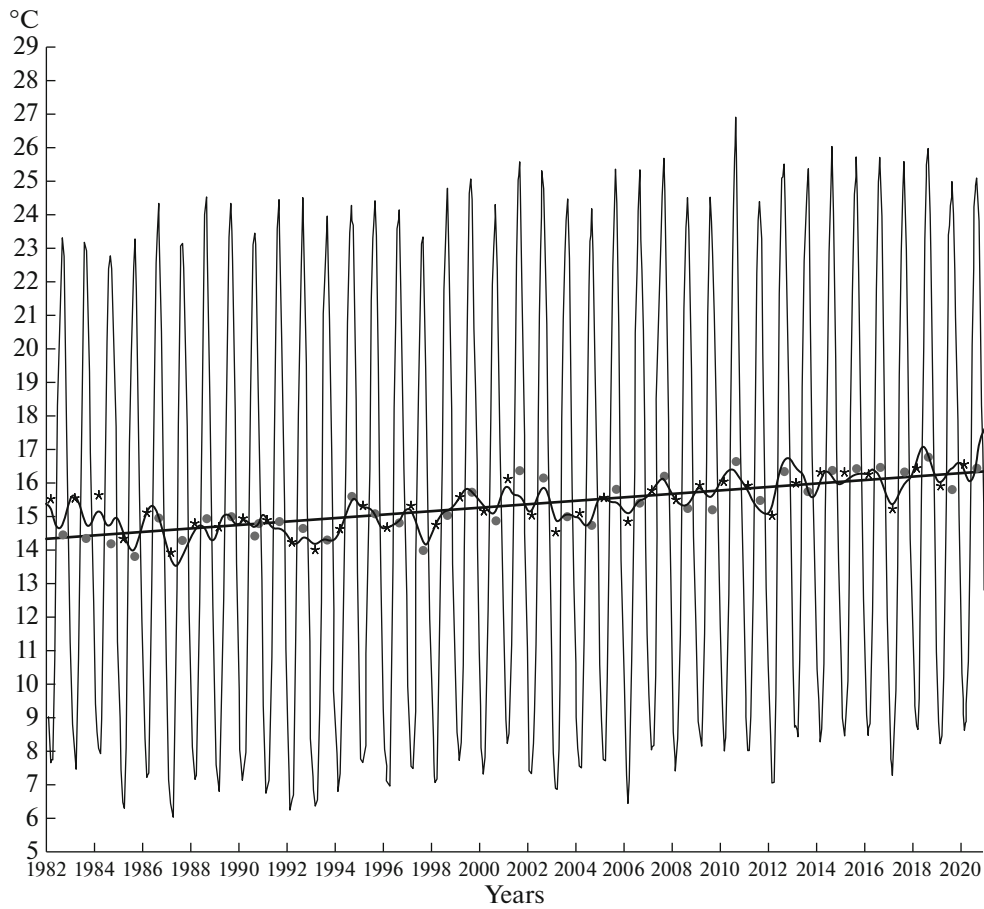
**Fig. 1.** Seasonal and interannual variability of mean monthly SAT ( $^{\circ}\text{C}$ ) for Black Sea–Sea of Azov region ( $40^{\circ}$ – $48^{\circ}$  N,  $27^{\circ}$ – $42^{\circ}$  E) in 1980–2020 (NASA MERRA-2). Black curved line—temperature anomalies smoothed by 1-year low-pass Butterworth filter; straight line—linear trend of these anomalies. Circles—average values of anomalies for summer (June–August); asterisks—for winter (December–February).

$0.005^{\circ}\text{C}/\text{year}$  [20]. Study [2] gives same estimate of the SAT trend of  $+0.05^{\circ}\text{C}/\text{year}$  based on data from a number of HMS located along the periphery of the Black Sea.

As follows from Fig. 1, since the late 1990s, the maximum monthly average summer SAT values on average increased markedly, with an extreme value of  $27.2^{\circ}\text{C}$  in 2010, when a blocking anticyclone remained over the central part of European Russia for 55 days from the end of June [24]. Since the late 1990s, the average and minimum winter monthly average SAT values increased; however, a more frequent recurrence of extremely low monthly average temperatures in the 2000s was also noticeable, with pronounced negative

anomalies (winters of 2002/2003, 2005/2006, and 2011/2012) versus the 1980s–1990s (Fig. 1). The winter of 2011/2012 was especially severe, when abnormally cold weather was observed in January and February in Central and Southern Europe, and for the first time in 80 years, the canals of Venice and piers of Lake Geneva were covered in ice [36]. The winter seasons of 1980/1981, 1998/1999, 2000/2001, 2013/2014, 2017/2018, and 2019/2020 were the warmest during the study period.

It is customary to subdivide winters on the Black Sea, depending on the amount of below-freezing days  $S$  according to measurements at coastal HMS, into three types [12, 2]: mild ( $S > -200^{\circ}\text{C}$ ), moderate



**Fig. 2.** Seasonal and interannual variability of monthly mean values of SST of Black Sea ( $^{\circ}\text{C}$ ) ( $41^{\circ}$ – $47^{\circ}$  N,  $27^{\circ}$ – $42^{\circ}$  E) in 1982–2020 (NOAA OI SST v2 high resolution dataset). Notation for anomalies and trend is the same as in Fig. 1. Circles—the average anomaly values for summer (July–September); asterisks—for winter (January–March) hydrological seasons.

( $S$  from  $-200$  to  $-400^{\circ}\text{C}$ ), and severe ( $S < -400^{\circ}\text{C}$ ). The winter of 2018/2019 was, in accordance with the estimate in [2, 3], extremely mild in the Black and Azov Seas ( $S = -66.5^{\circ}\text{C}$  in the northwestern Black Sea and  $-63.7^{\circ}\text{C}$  in the Sea of Azov and Kerch Strait). Mild winters in the 2000s also include those of 2000/2001, 2006/2007, 2014/2015, 2015/2016 [13]. Judging from Fig. 1, the winters of 2017/2018 and 2019/2020 were also warm. The average air temperature in the winter of 2018/2019 in the Black Sea–Sea of Azov region was, according to [3],  $2.7^{\circ}\text{C}$  above the norm.

#### *SST of the Black and Azov seas*

The SST in the Black Sea, like the SAT (Fig. 1), has significantly increased over the period under consideration (Fig. 2). Maximum monthly average summer and minimum winter SST values since the end of the 1990s increased on average: summer highs in most cases exceeded  $25^{\circ}\text{C}$  with an extreme of  $26.94^{\circ}\text{C}$  in August 2010; in the last decade of the 2000s winter lows in most cases did not fall below  $8^{\circ}\text{C}$ . In contrast to the mid-1980s–early 1990s, only in the winter of

2006 the minimum mean monthly SST significantly dropped below  $7^{\circ}\text{C}$  ( $6.42^{\circ}\text{C}$  in February). The maximum summer and minimum/maximum winter SST values correspond to approximately the same years as for the SAT. The lowest winter temperatures in these years were recorded in 2003, 2006, 2008, 2012, and 2017.

The linear SST trend for the 39-year period of 1982–2020 (Fig. 2) was  $+0.052^{\circ}\text{C}/\text{year}$ . This estimate agrees well with the values of the Black Sea SST trends in studies by other authors in close time periods:  $+0.052^{\circ}\text{C}/\text{year}$  in 1995–2015 [37],  $+0.040^{\circ}\text{C}/\text{year}$  (September 1981–November 2015) [25],  $+0.072^{\circ}\text{C}/\text{year}$  based on Gelendzhik HMS data [20] in 1987–2017 (for 82 years, 1935–2017, it was approximately half that,  $+0.031 \pm 0.005^{\circ}\text{C}/\text{year}$ ). The estimate of the temperature trend of the surface layer of the Black Sea  $+0.07^{\circ}\text{C}/\text{year}$  is given in [2].

The average annual SSTs of the Black Sea over the considered 39-year period are shown in Fig. 3 (linear trend of SST  $+0.052^{\circ}\text{C}/\text{year}$ ). The average annual SST, which practically did not exceed  $15^{\circ}\text{C}$  in the 1980s–early 1990s, in 2018, 2019, and 2020 reached  $16.71$ ,

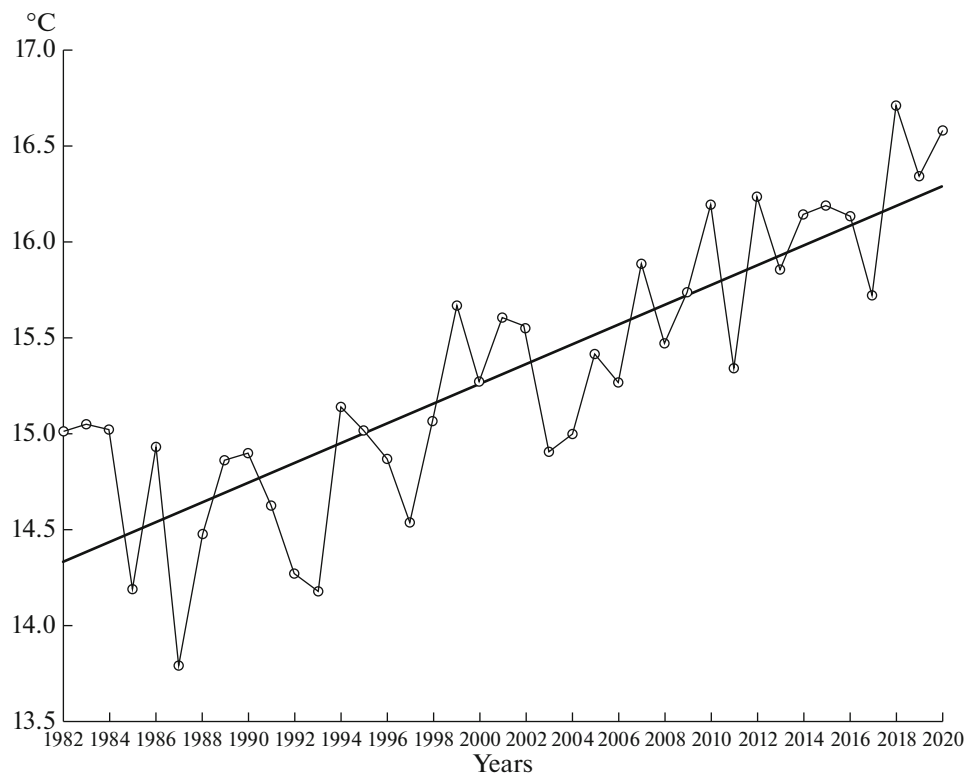


Fig. 3. Average annual values of SST of Black Sea (°C) in 1982–2020. Straight line—their linear trend.

16.34, and 16.58°C, respectively. These values agree well with the measurements at the HMS in 2019 [2]: the annual average SST values on the Crimean coast in Sevastopol, Yalta, and Alushta were 16.6, 16.1, and 16.2°C, respectively, which is 1.6, 1.6, and 1.5°C higher than the long-term average; a lower SST value of 15.2°C, 2.1°C higher than the average annual, was recorded in Feodosia, where the effect of the Sea of Azov waters is significant [13]; in the northeastern Black Sea, there are higher average annual SST values: 16.6°C in Novorossiysk, 17.1°C in Tuapse, and 17.5°C in Sochi, which is 1.6, 1.3, and 1.4°C, respectively, higher than the long-term average. The range of variations in the average annual SST of the sea as a whole in 1982–2020, with a maximum in 2018 and a minimum in 1987 (13.79°C), was 2.92°C (Fig. 3).

SST trends are unevenly distributed over the Black Sea (Fig. 4). The highest values (+0.058–0.060°C/year) are observed along the northeastern coast; the minimal values (less than +0.044°C/year) are in the center of its western part (in the area of the western cyclonic gyre) and in the northernmost part of the northwestern shelf. Roughly the same distribution pattern of SST trends over the sea area for 1981–2015 is presented in [25]. In the northeastern part of the sea in 1983–2015, SST trends were recorded within +0.075–0.084°C/year [35]. Differences in the regional trends of the average annual SST of the Black Sea estimated for 1982–2009 were also noted earlier in [5, 16, 30]: in the Kerch,

northeastern, and near-Bosporus regions, the SST trends were +0.08, +0.06, and +0.05°C/year, respectively, with the trend for the sea as a whole of +0.06°C/year.

The distribution of SST trends over the water area is associated with the physical–geographical and hydrological features and water dynamics in different parts of the Black Sea. The northeastern region is influenced by warm waters of the Black Sea Rim Current moving to the northwest and the formation/propagation of mesoscale anticyclonic eddies in the direction of the Rim Current. In addition, in the area 43–44° N on the Caucasian coast and near the Anatolian coast, anticyclonic eddies often detach and transform into open sea eddies [44], which possibly causes the bend in the isoline of the 0.56°C/10-year trend towards the center of the eastern part of the sea in Fig. 4.

The nature of the variation in the average annual SST values over time in the Black and Azov Seas is on average the same [5, 16]. According to Dashkevich and Kulygin [9], in 1982–2015, an increase in the average annual SST (on average) in the Sea of Azov itself and in Taganrog Bay was observed; the increase in 2000–2015 versus 1982–1999 averaged 0.95°C in the sea and 0.84°C in the bay. An increase in the average annual SST was observed from the mid-1990s to 2010 (trends of +0.05°C/year in the sea itself and +0.04°C/year in the bay); then, until 2015, a slight decrease was observed. The highest average annual SST in 1982–

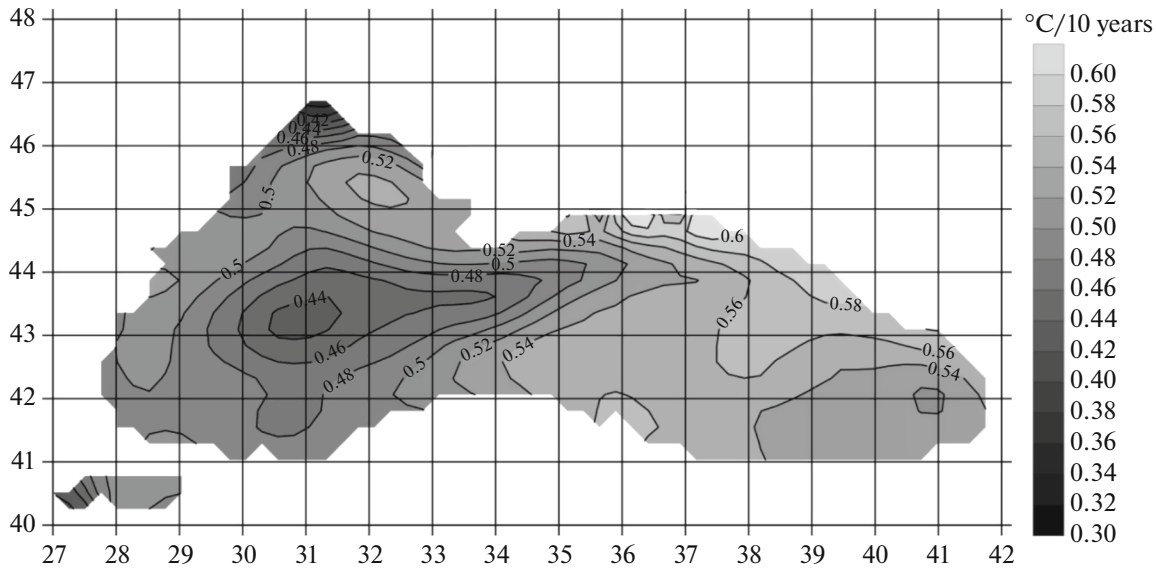


Fig. 4. Distribution of SST trends over Black Sea water area ( $^{\circ}\text{C}/10$  years) in 1982–2020.

2015, corresponding to 2010, was approximately  $13.7^{\circ}\text{C}$  in the sea itself and  $13.4^{\circ}\text{C}$  in Taganrog Bay, while the average annual SST of the Black Sea in 2010 was  $16.19^{\circ}\text{C}$  (Fig. 3), i.e.,  $\sim 2.8^{\circ}\text{C}$  higher than the average annual SST of the Sea of Azov. In 2019, the average annual SST in Taganrog Bay was  $13^{\circ}\text{C}$  [3]; therefore, in the Sea of Azov itself, it was several tenths of a degree higher (within  $0.7^{\circ}\text{C}$ , as comparison of the data in [9] shows). In the Black Sea in 2019, the average annual SST was  $16.34^{\circ}\text{C}$  (Fig. 3). This and the comparison performed in [5, 16] of the average annual SSTs of the Black and Azov Seas shows that the difference between them in different years is  $2\text{--}3^{\circ}\text{C}$ .

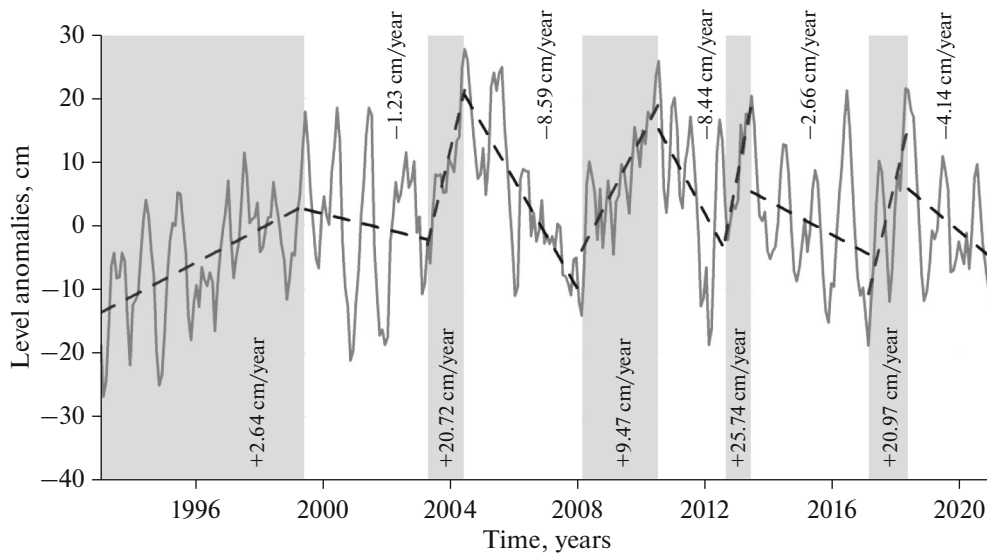
#### *Levels of the Black and Azov Seas*

Figures 5 and 6, respectively, show interannual changes in the level anomalies of the Black and Azov Seas according to data of along-track altimetry measurements of the T/P and J1/2/3 satellites in 1993–2020. The long-term variability of the Black Sea level is characterized by alternating rise and fall periods. As well, in different time intervals, the rate of rise in level varied from a minimum of  $+2.64$  cm/year from January 1993 to June 1999 to a maximum of  $+25.74$  cm/year from August 2012 to July 2013; the rate of the drop in level varied from  $-1.23$  cm/year from June 1999 to April 2003 to  $-8.59$  cm/year from June 2004 to February 2008. The 1993–2020 average linear trend of  $+0.32 \pm 0.16$  cm/year was approximately 2.5 times lower than in 1993–2012 ( $+0.82 \pm 0.18$  cm/year), although 1.5 times greater than from the 1920s to the mid-1990s ( $0.17\text{--}0.18$  cm/year) [14].

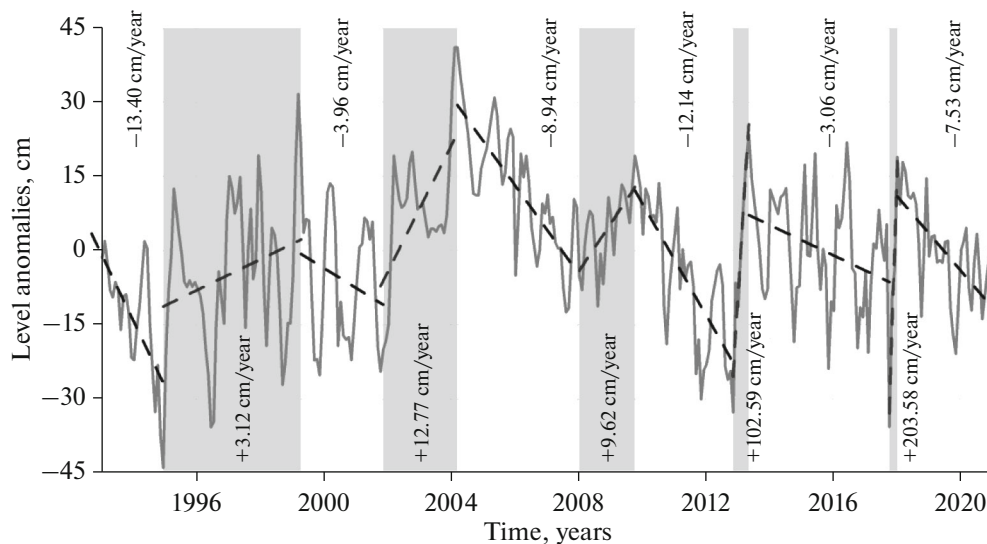
The lower value of the trend for the period spanning the 2010s is associated with the change in the trend of sea level change from its rise (on average) to a

certain decrease (on average) from about 2004–2010; the time intervals with an increase in level became shorter, and with a decrease, longer (Fig. 5). The decrease in the overall positive trend in level in the period spanning the 2010s is also significant according to the results of other publications. Whereas in 1992–2005, according to the data in [15], the trend of the Black Sea level was estimated at  $+0.76 \pm 0.03$  cm/year, in 1993–2014, it was  $+0.31$  [33] and  $+0.32 \pm 0.08$  cm/year [25]; from January 1993 to May 2017, it was  $+0.25 \pm 0.05$  cm/year [26].

Note that the local values of the level trend differ from those given for certain periods of the average for the sea as a whole, which is associated with the peculiarities of the large-scale and mesoscale dynamics of the sea [33]. Thus, due to the intensification of the Rim Current in 1992–2005, the rate of level rise in coastal areas of the sea,  $+0.8\text{--}0.95$  cm/year, was 1.5–2 times higher than in its deep-water part, with a mean trend of  $+0.76 \pm 0.03$  cm/year for the sea [15]. The 1993–2014 average positive level trends varied from a maximum of  $+0.34$  cm/year in the southeastern part to a minimum of  $+0.3$  cm/year in the area of the eastern cyclonic gyre [25]. According to [33], the 1993–2014 average rate of level rise varied from  $+0.15$  cm/year in the central part of the sea to  $+0.35\text{--}0.38$  cm/year at its periphery and above the shallow northwestern shelf and to  $+0.5$  cm/year in the southeastern part. The values of the level trend of  $+0.24\text{--}0.32$  cm/year for 1993–2015 were obtained off the coast of Krasnodar krai and Abkhazia [35], with a minimum of  $+0.16\text{--}0.18$  cm/year in the deep-water eastern part. On the distribution of the mean level trends for 1979–2017 over the sea area, constructed at the Climate Center of the University of Hamburg and presented in [2], the values vary from



**Fig. 5.** Changes in Black Sea level anomalies (cm) from January 1993 to December 2020 according to altimeters of T/P and J1/2/3 satellites (solid line). Dotted line—interannual variability of their mean values. Periods of rise in level are shown in gray.



**Fig. 6.** Changes in the level anomalies of Sea of Azov (cm) from January 1993 to December 2020 according to altimeters of T/P and J 1/2/3 satellites. Notation is the same as in Fig. 5.

0.225 cm/year at the periphery to 0.175 cm/year at the center of its eastern part.

Note that the difference in the values of the Black Sea level trend in different studies is due to their use of different data. Thus, for our studies, we used along-track data, whereas in [15, 25, 33], level anomaly maps were used constructed on a regular grid with a resolution of  $0.125^\circ$  in latitude and longitude based on altimetry measurements of not only T/P and J1/2/3, but also other satellites, e.g., ERS-1/2 and ENVISAT. The procedure of optimal interpolation itself used to create maps of level anomalies introduces errors into the satellite measurement data. Level anomaly maps

are constructed for every day, but due to a peculiarity of satellite altimetry data (recurrence of measurements along tracks once every 10 days), there are gaps; i.e., on some days, satellite altimetry data for the Black and Azov Seas are simply not available.

The 1993–2020 average rate of rise in the level of the Sea of Azov (Fig. 6) is  $+0.21 \pm 0.05$  cm/year. That is, the linear trend of the level rise in 1993–2020 decreased by about 2.6 times compared with the values given in [14] for 1993–2012 ( $+0.54 \pm 0.04$  cm/year) and almost reach the trend recorded from the 1920s until 1985 ( $+0.24$  cm/year). The transition from sea level rise (on average) to a decrease, with alternating

relatively short time intervals of sea level rise and longer intervals of sea level decrease, took place in 2004 (the year of the maximum sea level anomaly). Thus, in both the Black Sea (from about 2004–2010) and Sea of Azov (from about 2004), a gradual decrease (on average) in sea level is observed. For the 28 years from 1993 to 2020, the Black Sea level rose by about 9 cm; the Sea of Azov level, by about 6 cm.

### *Ice Cover*

The ice regime of the Black and Azov Seas is characterized by significant interannual variability. In the Black Sea, ice appears mainly on the shallow northwestern shelf, in the Kerch Strait, and on the Kerch shelf. Due to synoptic variability of atmospheric processes, wind-wave impact, and advection of warm waters, in these shallow areas with low heat storage in the winter season the recurring appearance and disappearance of ice is possible [2]. Ice cover in them is closely related to the total negative average SAT for the ice season (the correlation coefficient for the northwestern part of the sea is 0.92 [2, 12]). In the 2000s, with an increase in the number of mild winters (Figs. 1, 2), there was a corresponding decrease in ice coverage. In the mild winter of 2018/2019, ice in the open regions of the northwestern part of the sea was not observed; it briefly appeared only in the Dnieper–Bug and Dniester estuaries and in the Tendra Bay [2]. However, in severe winters, the area covered by ice increases significantly. In the severe winter of 2011/2012, the sea was covered with ice in Kerch, Evpatoria, Novorossiysk, Odessa, and Constanta [14]. The entire Gulf of Odessa, the Dnieper–Bug estuary, the Kerch Strait, the coasts of Romania and Bulgaria, and the Danube were frozen; navigation on the Bosphorus was halted [7]. In the cold winter of 2005/2006, freezing of the bays of Sevastopol was even greater than in 2012 [7]. In the Kerch Strait, in addition to ice of local origin, under the influence of wind and currents, ice from the Sea of Azov can appear, and in the Kerch region of the Black Sea (sometimes near Feodosia),—ice transported from the Kerch Strait [2].

In the shallow Sea of Azov, with a lower salinity and heat storage versus the Black Sea, ice appears annually, even in relatively mild winters [3]. As follows from Fig. 7, the ice cover in the Sea of Azov in 1980–2020 decreased on average (the linear trend is  $-1.2\%/10$  years). The 2000s witnessed an increase in number of winters with the highest average monthly ice coverage of less than 10%, which corresponds to an increase in the number of mild winters in these years (Figs. 1, 2). This is confirmed by observations [3]: in the winters of 1980/1981, 1989/1990, 2000/2001, 2006/2007, 2014/2015, 2015/2016, and 2018/2019, there was practically no ice in the Sea of Azov (e.g., in the winter of 2018/2019, only the initial types of ice were recorded, mainly in Taganrog Bay). The greatest ice coverage was observed in the cold winters of

2002/2003, 2005/2006, 2007/2008, and 2011/2012. (Fig. 7).

The nature of the ice distribution in the Kerch Strait based on satellite data from 1999 to 2017 was considered in [17]. It was demonstrated, in particular, that in February 2012, the year with the greatest ice coverage for 1980–2020 (Fig. 7), the distribution of the southern boundary of the ice cover in the strait was the greatest for the entire observation period since 2000. In the warm winters of 2014/2015 and 2015/2016, with practically no negative SAT, only insignificant fast ice was recorded along the Chushka Spit and in Taman Bay.

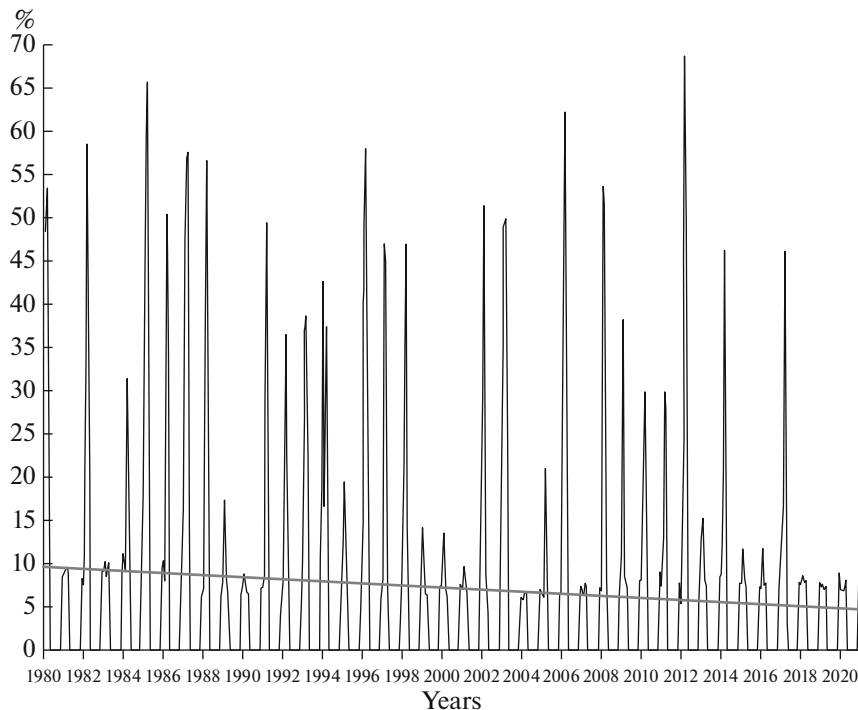
In [10], modeling, observations in ports, and satellite images were used to demonstrate that the average ice cover of the Sea of Azov for the winter season in the first 16 years of the 21st century (16%) was approximately half that in the mid-20th century (30%). In 2005/2006–2015/2016, the greatest ice coverage was observed in the coldest winters of 2005/2006 and 2011/2012 (approximately 32 and 36%, respectively); the least, in the mild winters of 2006/2007 and 2015/2016 (less than 5%); the ice thickness was about 22 cm in these cold winters and 4 cm in the mild. In the winter of 2002/2003, which, according to estimates in [23], was even harsher in the Sea of Azov than the winter of 2011/2012, the ice cover reached approximately 45%. However, the ice concentration of the coldest winters in the first 16 years of the 21st century was significantly less than the maximum ice cover of winters in the early–mid-20th century, which often exceeded 50%, and in the most severe for the entire observation period of 1885–2015 winter of 1953/1954 [23] reached approximately 68% (with a comparable average ice thickness). The greatest ice thickness (up to 50 cm) was observed in Taganrog Bay.

According to the graphs presented in [23], from 1950 to 2015, the onset of the ice period in ports of the Sea of Azov, on average, shifted towards later dates, and the end, towards earlier ones. Thus, the beginning of freeze-up in Taganrog shifted on average from mid-November in 1950 to mid-December in 2015, and the end, from the first days of April to mid-March; in Kerch, the shift in dates of the beginning and end of freeze-up is from the second half of December to early January and from mid-March to mid-February, respectively. Thus, the average duration of the ice period over these 66 years, estimated by us from the linear trends given in [23], has significantly decreased (by about 1.5 months).

## DISCUSSION AND CONCLUSIONS

Our analysis of climate change in SAT of the Black Sea–Sea of Azov region (1980–2020) and SST of the Black Sea (1982–2020) using NASA MERRA-2 satellite datasets [29] and the NOAA OI SST v2 high resolution dataset [38], respectively, as well as a comparison of the obtained temporal variability of the average





**Fig. 7.** Changes in average monthly ice concentration in Sea of Azov (%). Straight line—linear trend ( $-1.2\%$  over 10 years) of these changes.

annual SST in the Black Sea with the available data on the SST of the Sea of Azov in different years [9, 3] showed that warming of these southern seas was observed throughout the entire period considered. The linear trend of the average annual SST in 1982–2020 in the Black Sea as a whole was  $+0.052^{\circ}\text{C}/\text{year}$ , and the average annual water temperature, since 2010, often exceeded  $16^{\circ}\text{C}$  (maximum  $16.71^{\circ}\text{C}$  in 2018). The character of the interannual variability of the SST of the Black and Azov Seas is, on average, the same. The average annual SST values of the Sea of Azov in different years are lower than those of the Black Sea by  $2\text{--}3^{\circ}\text{C}$ .

It should be noted that against an increase in SAT and SST in the considered period, their values in the 2000s differ markedly from those in the 1980s–1990s. The maximum average monthly summer and minimum winter SAT (Fig. 1) and SST (Fig. 2) values increased, and the number of mild winters increased. The consequence of an increase in winter temperatures in the Black Sea was only episodically replenished waters of the cold intermediate layer (CIL) with a temperature of less than  $8^{\circ}\text{C}$  and, accordingly, a decrease in the oxygen content in this layer [27, 37, 39]. Since 2005, only in 2006, 2012, and 2017 (years with minimal winter SST, Fig. 2) CIL waters were significantly replenished [39, 27]. Whereas from 1954 to 2009, the temperature in the CIL core slightly exceeded  $8^{\circ}\text{C}$  only in 1962 and the minimum values in 1954 and 1987 were less than  $6.2^{\circ}\text{C}$  [30, 14], in the 2000s, replenishment of CIL waters had an intermittent character: its tempera-

ture often exceeded  $8^{\circ}\text{C}$ , and in 2015–2017, it reached  $8.7^{\circ}\text{C}$  [39]. An increase in the number of mild winters resulted in a decrease in ice concentration in the Sea of Azov (Fig. 7), and in some winters, there was almost no ice cover. Obviously, the forecast in [11] on the expected harshest ice conditions in the 2018/2019 ice season in the Sea of Azov did not come about.

Whereas the trend of the continued increase in SAT/SST in the Black and Azov Seas is consistent with global warming, the trends in the level of these inland seas in the 2000s do not correspond to an increasing rate of rise in the level of the World Ocean. From about 2004–2010 in the Black Sea and 2004 in the Sea of Azov, their levels have been decreasing on average, while maintaining positive trends in 1993–2020 ( $+0.32 \pm 0.16$  cm/year in the Black Sea and  $+0.21 \pm 0.05$  cm/year in the Sea of Azov). The reason for this decrease in level (on average) in the last 10–15 years is apparently a decrease in the incoming part of the freshwater balance (river runoff and atmospheric precipitation, although an increase in evaporation is also possible, associated with an increase in the of water and air temperatures [2]). In [31, 32], it was noted that in 1993–2009, the rise in the level of the Black Sea in 1993–1999 and its drop in 1999–2002 (see Fig. 5 above) corresponded to an increase/decrease in Danube runoff in these years, while from 2003 to 2009, no such correlation was observed.

An indirect indicator of a decrease in the freshwater balances of these seas is the increased salinity of their

waters. According to [2], an increase in salinity has been observed in the Black Sea at an average rate 0.04‰/10 years. The average annual salinity of the surface layer in Novorossiysk and Tuapse in 2019 exceeded the norm by 1.04–1.35‰. In the Sea of Azov, an increase in salinity has been observed since 2007, associated with the low water level of the Don and a decrease in atmospheric precipitation (by 33–194 mm at different points with respect to the long-term average annual norm of 460 mm) [3]. Salinity in the open parts and coastal zone of the Sea of Azov in 2019 reached its maximum values for the entire historical period of observations, which has had a detrimental effect on the ecological situation in the sea [3].

The question of a relationship between changes in the levels of the Black and Mediterranean Seas has not yet been sufficiently studied. Study [42] demonstrated the same character of changes in the levels of the Black and Aegean Seas in 1993–2003: their rise in 1993–1999 and drop in 1999–2003 (see Fig. 5 above). It was suggested that the increase in the SST (steric factor) was the determining factor in the rise in levels of these seas before 1999. The calculation in [41], conversely, shows that the change in steric heights does not explain the observed changes in level of the Black Sea. In [43], a high (0.75) correlation was found between nonseasonal (with the average monthly climatology excluded) time sequences of level anomalies in the Black and Aegean Seas, with a 1-month lag of Black Sea anomalies with respect to the Aegean, which suggests the influence of some general dynamic factor on the levels of both seas. An assumption was made about the influence of large-scale atmospheric circulation associated with the North Atlantic Oscillation on changes in levels of the Mediterranean and Black Seas via wind impact, respectively, near the Strait of Gibraltar and over the Aegean Sea/Turkish straits. The latter can change the level gradients along the Turkish straits and, therefore, affect the expenditure part of the Black Sea water balance: the outflow of Black Sea waters through the Bosphorus Strait and, accordingly, sea level. The fact of wind impact on water exchange in the Bosphorus Strait, up to the blocking of upper Bosphorus/lower Bosphorus currents by southerly/northerly winds, respectively, has long been well known (see, e.g., [4, 34]); however, there are no statistics on the frequency and duration of such events over the years, and their contribution to the interannual sea level variability is unknown.

#### FUNDING

A.I. Ginzburg performed research under state task no. 0128-2021-0002 “Mechanisms of the Formation of Circulation Structures in the World Ocean: Key Processes in the Boundary Layers and Their Role in Ocean Dynamics Based on Expeditionary Research, Remote Sensing, and Numerical and Laboratory Simulation.” Data on the Sea of Azov and Kerch Strait were analyzed by A.G. Kostianoy

and I.V. Serykh with support of the Russian Science Foundation, grant no. 21-17-00191 “Monitoring of Water Exchange through the Kerch Strait Based on Modern Observation Methods and Numerical Simulation” (2021–2023). S.A. Lebedev analyzed satellite altimetry data as part of budgetary funding of GC RAS.

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